TITLE OF THE THESIS

Experimental Studies on Fused Deposition Modeling Process for Microturbine Impeller Application

INTRODUCTION

The combustion of fossil fuels to meet the ever-increasing demand for energy was a major contributing anthropogenic activity to climate change. Fossil fuel resources were non-renewable and limited in supply. These issues promoted the need for effective use of non-renewable energy sources through the improvement of existing energy systems and the application of emerging technologies for harvesting renewable energy sources. Sustainable development at a global level also encouraged use of newer, clean energy systems and the efficient utilization of existing energy systems.

Microturbines were energy generators that have a significant role to play in the field of power generation. Microturbines can potentially be employed in both renewable and non-renewable energy fields due to their suitability for low and medium-grade heat energy.

Organic Rankine Cycle (ORC) was one of the promising technologies for converting low or medium-grade heat energy into useful power generation. It worked similar to a steam rankine cycle, with all the same components such as pump, compressor, heat source, expander, and condenser. The major difference between these two cycles was in the type of working fluid used during the operation: the steam ranking cycle used water, and the ORC used organic compounds as working fluid, hence the name organic. ORC-based applications built with traditional manufacturing often faced higher production costs and lead times. Also, traditional manufacturing processes lack the flexibility needed for the customization of ORC applications. This led to the utilization of AM processes for developing ORC components.

Additive manufacturing (AM) was a versatile manufacturing method, also known as layered manufacturing that entails the development of complex three-dimensional (3D) objects. There are many applications of AM across different industrial sectors including power generation, aerospace, and medical. With the advent of material science and relevant technologies, various

AM techniques such as binder jetting, material jetting, directed energy deposition, powder bed fusion, material extrusion, photopolymerisation, and sheet lamination were utilized for manufacturing the functioning parts quickly.

Fused deposition modeling (FDM), also generically referred to as the fused filament fabrication (FFF) method was a material extrusion-based AM process. Due to simplicity, flexibility, cost-effectiveness, and ease of control over process parameters, FDM gained widespread popularity among AM practitioners.

In the FDM process, computer-aided design (CAD) models of 3D objects were initially sliced by slicing software to convert 3D model details into printing instructions in form of tessellation file format (STL). Raw materials in the form of polymer filaments unwound from the material spool into a heated nozzle for requisite extrusion. The viscous polymer extrudate was deposited on to the build platform through a small-diameter nozzle. This nozzle moved along a path that is predefined, and preprogrammed by motion control codes referred to as G-codes. One deposited layer of the extrudate is followed by the subsequent deposition of the next layers, resulting in the printing of the parts layer-by-layer.

STATEMENT OF THE RESEARCH PROBLEM

The mechanical behavior of FDM-build parts has faced challenges due to residual stress. In addition, the FDM process is also affected by warpage. Another challenge associated with the FDM process is the selection of material for particular application. Despite the effectiveness of the FDM process, many factors impact the quality and functionality of FDM-build parts. The major control parameters include slice height, infill density, infill pattern, infill angle, shell thickness, build orientation, print speed, and temperature, all of which affect the microstructure and, eventually the performance of the parts. Though technological barriers exist, as in most technology areas, it is important to overcome them by developing a proper understanding of processes and their related attributes. This leads to framing the research problem statement as: Can the FDM process be utilized optimally for the manufacturing of microturbine impellers?

In this direction, an experimental investigation is conducted to improve the applicability of the FDM process for the manufacturing of ORC microturbine impellers. Initially, the problem to be addressed during the literature review was specified in the form of comprehensible and

structured questions. This helps in defining the pathway for a systematic review. Simply put, the framing of these questions clarifies the motive for conducting the literature survey. Two review questions were framed as:

1. What is the current level of adoption of the FDM process in the manufacturing of microturbines?

2. What are the challenges and future research directions toward the development of higher-level adoption of FDM in the manufacturing of the microturbines?

RESEARCH OBJECTIVES

This work emphasizes the FDM process functionality to understand the multiple interacting phenomena involved and to make it as reliable and predictable as conventional manufacturing processes. Based on these guiding principles, objectives of the present research are as follows:

- To develop a numerical model of the FDM-built impeller using numerical simulation tool
- To investigate the impact of process parameters on dimensional accuracy, surface finish, manufacturing time, and material consumption
- To determine the relationship between process parameters and response parameters
- To optimize and validate the process parameters for microturbine impeller manufacturing

NATURE AND SCOPE OF THE WORK

A systematic analysis of the organic rankine cycle was performed to identify important operational parameters. Consequently, the mean line design methodology was utilized to design the impeller of radial inflow turbine. For this foundational design work, Ansys Vista RTD and Ansys BladeGen softwares were utilized, which facilitated the preliminary design of the impeller to satisfy the necessary performance criteria. Then, Ansys DesignModeler software was employed to refine the impeller design. However, a smaller impeller model was used to simplify the optimization process. This approach helped in conducting well-organized experimental trials and ensured that adjustments to the impeller design allowed the smaller impeller model to retain the desired characteristics while being suitable for 3D printing.

A numerical model of the impeller was developed using simulation software Digimat to predict the response of the FDM-built impeller in terms of warpage, residual stress and deflection. This model helps in developing the understanding of the mechanical behaviour of the 3D printed impeller. It facilitated the insights into potential warpage, residual stress and deflection patterns, which significantly impact the structural integrity and performance of the impeller.

RESEARCH METHODOLOGY

This work investigated three levels of each input parameter in combination of slice height (0.127 mm, 0.1778 mm, 0.254 mm), infill density (25%, 65%, 100%), and infill angle (0°, 45°, 90°). Parameter and there ranges were selected based on existing research studies, identified gaps in literature survey, results of simulation study, and constraints of the printer. In full factorial design of experiment (DOE) approach, experimental runs were performed for every combination of the factor levels. In this work, full factorial design methodology was used for conducting the 27 experiment runs. A full factorial design included all possible combinations of a set of factors. Full factorial experiments were the vital means to completely and systematically study interactions between factors in addition to identifying significant factors. This was the fool proof design approach, but it was also the most costly in experimental resources. Performance parameters, including dimensional accuracy, surface finish, printing time, and material consumption were thoroughly measured using specialized tools: Coordinate Measuring Machine (CMM) for dimensional accuracy, Surface Roughness Tester for surface finish evaluation, Stopwatch for printing time, Digital Weighing Balance for material consumption.

Impellers were manufactured using ASA (Acrylonitrile Styrene Acrylate) material with a Stratasys F170 printer. Statistical techniques, including ANOVA, surface regression models, main effect plots, contour plots, and surface plots, were employed to analyze the data. Response Surface Methodology (RSM) optimization technique was utilised to identify the optimal printing parameters.

CONTRIBUTION MADE TO THE EXISTING KNOWLEDGE

Optimum parameter settings identified were a slice height of 0.127 mm, an infill density of 25%, and an infill angle of 90°. Confirmation experiments were conducted to validate these optimization results. The predicted values were 3.764 μm and 4.375 μm for surface finish (Ra_F

and Ra_B), 0.27% dimensional accuracy (ΔD) as deviation, 231.01 minutes for printing time (PT), and 15.312 grams material consumption (W). The experimental results obtained were 3.527 µm for Ra_F, 4.681 µm for Ra_B, -0.01 % deviation for ΔD, 265 minutes for PT, and 14.21 grams for W. The corresponding error percentages were -0.067%, 0.065%, 1.157%, 0.128%, and -0.078% respectively. The minimal error percentage highlights the strong agreement between the experimental results and predicted values, validating the accuracy of the optimization.

To validate the dimensional accuracy of the impeller, optical metrology tools were employed for precise data acquisition. The impeller was scanned by a 3D scanner to compare the scanned data with the CAD model of the impeller. After marking and positioning of the impeller on the rotary table, multiple scans were taken from all sides to accurately capture its profile and dimensions. The scanned model was overlapped and aligned with the CAD model of the impeller for a detailed comparison. Dimensional accuracy was analysed by determining the deviation between these two models, with results demonstrated in different color codes. The deviations were within the allowable tolerance range of 0.4 mm; thus validating the dimensional accuracy of the impeller manufactured by the FDM process.

Fifteen ASTM (American Society for Testing and Materials) specimens were manufactured with optimised setting indicated by RSM optimization: Five tensile, five compressive, and five flexural Specimens. These samples were categorized as A, B, C, D, and E Specimen. Measurement of weight, dimensional accuracy, and surface finish were conducted for all specimens. Then, specimens B were immersed in water for one day, and specimens C were immersed in ethanol for one day and then again its weight, dimensional accuracy, surface finish and its strength was checked.

Similarly, specimens D were immersed in water for seven days, and specimens E were immersed in ethanol for seven days and then again its weight, dimensional accuracy, surface finish and strength were checked. Results indicated no significant impact on the weight, dimensional accuracy, and surface finish and strength before and after immersion. Tests for checking tensile strength, compressive strength and flexural strength were conducted on UTM machine.

CONCLUSION

This research work has significantly advanced the technological readiness level of the FDM process for manufacturing microturbine impellers. The investigation focused on the manufacturing of impellers for an ORC system, utilising a full factorial approach to print 27 impellers. The process was systematically optimised to achieve the defined research objective, thereby demonstrating the potential of the FDM process in microturbine impeller manufacturing.

In this work, a numerical model was developed using numerical simulation software Digimat to predict warpage, residual stress and deflection induced during the manufacturing of impellers with FDM process. The simulation results exhibit a significant impact of layer thickness and infill density on output parameters, providing better understanding of the mechanical behavior of 3D printed parts.

Experiments conducted with a full factorial approach revealed that layer thickness had a significant impact on dimensional accuracy. Increasing the layer thickness from 0.127 mm to 0.1778 mm leads to gradual reduction in dimensional accuracy and when layer thickness is increased further to a higher level of 0.254 mm, dimensional accuracy is slightly improved. However, highest dimensional accuracy is achieved with lower layer thickness of 0.127 mm.
Higher surface finish of micro turbine impeller was observed at layer thickness of 0.127 mm and infill density of 20%. Layer thickness was significantly impacting the surface finish and its impact evident from the main effect plots which demonstrated that increasing layer thickness from 0.127 mm to 0.1778 mm leads to lower surface finish. Layer thickness and infill density was significantly impacting the manufacturing time and material consumption as evident from the lower P-value. Thicker layers resulted in reduced manufacturing time for the microturbine impeller. Less material was consumed when the layer thickness was 0.127 mm and the infill density was 20%.

Empirical relationship between FDM process parameters and output parameters selected in this study was developed by using surface regression model. Coefficient of determination R^2 For output parameter such as manufacturing time, material consumption, Surface finish_Front, Surface finish_Back and dimensional accuracy was 99.93%, 98.51%, 78.51%, 88.84%, and

74.62% respectively. Additionally, Main effect plots, interaction plots, diagnostic plots, and surface plots were employed for statistically analysing the empirical relationship between process parameters (Layer thickness, infill density and infill angle) and all output parameters.

Layer thickness (0.127 mm), infill density (25%), and infill angle (0°) were identified as optimal settings and it was validated through confirmatory experiments. The results of confirmatory experiments revealed minimal deviation between predicted and experimental values. This optimal combination of process parameters resulted in a dimensional accuracy deviation of just 1%, confirming the robustness of the optimization process. 3D scanning techniques were utilised to validate dimensional accuracy by comparing the CAD model with a scanned model of the impeller.

Mechanical performance assessed through UTM tests (tensile, compressive, and flexural strength) along with chemical compatibility tests confirmed the strengths and durability of the FDM parts, without any significant changes in mechanical performance, appearance or chemical compatibility after immersion in water and ethanol.

These conclusions confirm that the objectives were achieved and the results obtained from this research work provide a solid foundation for future studies to advance the technological readiness level of the FDM process for manufacturing microturbine impellers.

ORGANISATION OF THESIS

Chapter 1 covers an introduction to the organic rankine cycle, radial inflow turbine, additive manufacturing and especially fused deposition modeling. It also consists of the motivation of the present work, research objectives, and structure of the thesis.

Chapter 2 consists of a literature review of existing research on the organic rankine cycle, mean line design, and adoption of fused deposition modeling process for manufacturing ORC parts. It identifies research gaps and sets up the scope of the current study.

Chapter 3 includes details of the methodology employed for conducting the research work. This covers the conceptual description of the mean line design of the turbine impeller, the development of a numerical model using Digimat, experimental setup, and RSM optimization.

Chapter 4 presents and analyses the experimental and simulation results, along with comparisons between predicted and experimental results in terms of surface finish, dimensional accuracy, printing time and material consumption. This chapter also covers the results of chemical compatibility tests.

Chapter 5 summarizes the key findings, major contributions, and limitations of the study and covers the scope for future research work. The report includes a listing of all the references cited throughout the thesis. It includes complete bibliographic details for journal articles, conference papers, books and other sources used in the research work.

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